TAPPING INTO URBAN RECYCLING FOR LOW-COST BUILDING ALTERNATIVES: Experimenting with Waste Cardboard Reuse in Architecture

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Abstract: The work presented in this paper is part of a research that explores upcycling waste corrugated cardboard into building components. The research focuses on developing countries where there is a vast low-income population that needs housing but who find standard construction systems unaffordable. The research involves observational studies on the work of cardboard pickers in Paraguay seeking to understand the cycle of waste cardboard in the local context; development of digital tools to design building parts with waste cardboard and generate their fabrication instructions; hands-on work in an academic setting prototyping and testing building parts; and experimenting with the building system in the target context through workshops. This article summarizes several lessons learned during a workshop developed with a group of waste cardboard collectors and discusses the potential alternatives to the shortcomings.

Keywords: Waste cardboard architecture, construction workshop, low-cost building parts

INTRODUCTION

Although the use of brand-new cardboard products in architecture has received considerable attention from researchers and practitioners in the last three decades and especially after the emergence of Shigeru Ban's paper tube structures, there is very little formal research focused on the direct reuse of waste cardboard (Latka 2017; Salado 2011; Pohl 2009; Ayan 2009). The situation is more noticeable in developing countries where the recycling rate of post-consumer goods is meager, and materials like waste cardboard are highly underutilized (Silpa Kaza, Bhada-Tata, and Van Woerden 2018)The work presented in this paper is part of a research that explores material workflow and tooling development for reusing waste cardboard with minimal transformations into building parts (Diarte and Shaffer 2018). The research is focused on developing countries where there is a vast low-income population that needs housing—but for whom using standard construction systems is unaffordable—and the recycling rate of urban solid waste is very low—Paraguay has one of the lowest recycling rates of the region according to (IADB 2015).

The research involves different tasks. The most important are; a) observational studies on the work of cardboard pickers in Paraguay seeking to understand the cycle of waste cardboard in the local context; b) development of digital design tools to help designers to configure building parts with sheets of waste cardboard collected from the urban waste stream; c) hands-on work in an academic setting prototyping and testing building parts for a construction system with waste cardboard and wood; and d) experimenting with the building system in the target context through workshops.

The content of this paper is focused on the results of the work developed during a construction workshop held in Asuncion, Paraguay, in August 2019. In this workshop, the researcher worked with waste cardboard collectors that do not have a formal education in construction but have easy access to the material through different collection methods.

The workshop had two primary goals. The first was to test the ease of fabrication of the parts and ease of assembly of a prototype unit. The second goal was to test the transferability of the system and evaluate the perception of the participants. For this reason, the participants—guided by the researcher—worked for five days repurposing 1.2 tons of waste cardboard in the fabrication of wall and floor panels made of cardboard and plywood frames. At the end of the workshop, the participants used the panels to assemble a prototype building unit.

This article summarizes several lessons learned during the workshop and propose alternatives to the shortcomings. Some of the lessons were, for instance, the workshop confirmed that waste cardboard is easy to get, inexpensive, workable, and that teaching the technology to the participants is viable. Nevertheless, the experience also showed that the use of plywood, sophisticated joints, and the inexperience of the participants can have a significant impact on the cost and the building capacity. Despite the limitations, the lessons learned with the workshop certainly adds to the understanding of the different disciplines involved when developing new building systems together with a local population.

1. DESIGN CONCEPT OF THE PROTOTYPE UNIT

1.1. PANELIZED SYSTEM

The construction system presented here is a continuation of a first prototype presented by Diarte, Shaffer, and Obonyo in 2019. In that paper, the prototype unit was fabricated with panels made of waste corrugated cardboard logs and repurposed plywood frames. Its fabrication and assembly were tested in an academic environment. This paper presents a variation of that first prototype. The concepts adopted for the design of this second prototype unit (PU2) were: off-site prefabrication, modular/incremental construction, and adaptability of the construction system.

The PU2, as shown in figure 1, is a container-like structure composed of floor, wall, and ceiling panels. The three types of panels have similar dimensions (600 mm width, 2400 mm long, and 136-150 mm thick) but different fabrication details. The dimensions follow the standard size of plywood boards—1200 x 2400 mm—and they are easily found in the target context.

The PU2 designed for the workshop is 4200 mm long (or seven panels of 600 mm), 2400 mm wide (length of the standard panel), and 2700 mm height. Although it has the size of a standard room (10 m2) the PU2 does not intend to represent a house typology yet. For this workshop, the existing floor was used as a foundation, and two wood studs of section 2 x 5 inches were placed as a transition between the unit and the floor. "Lifting" the PU2 from the floor using these wood studs would also help to avoid potential humidity problems due to capillary rise.

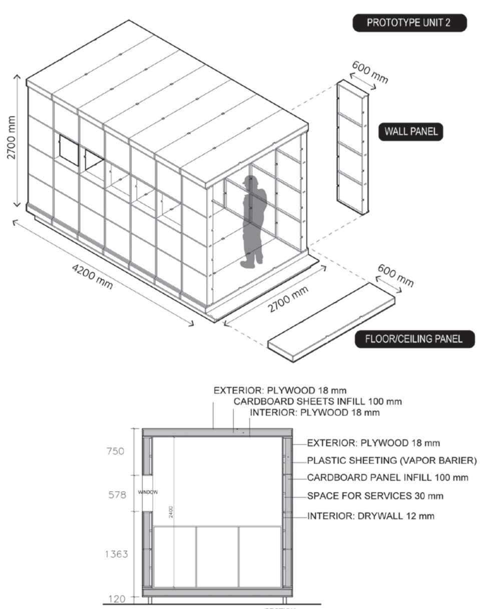

Figure 1: Prototype Unit (Author 2019)

1.2. FABRICATION OF THE PANELS

The panels have three main parts: frame, infill, and facing. The frame is fabricated with 18 mm plywood cut with conventional carpentry tools and/or a CNC router—if available—and then manually assembled using electric power tools and wood screws. Finger joints help to assure the connection between the pieces. The frame for the wall panel is composed of two vertical studs of 18 x 150 x 2400 mm each and four horizontal battens of 18 x 600 x 150 mm each that create four niches of 577 x 564 x 15 mm for the cardboard infill (figure 2a). For this experiment, all wall panels are the same; however, the design can have other configurations. The wood frame for the floor/ceiling is composed of two studs of 18 x 150 x 2400 mm each and two battens of 18 x 600 x 150 mm each. These frames did not have intermediate battens, but the assembly method is similar to the frames for the wall (figure 2c).

There are two versions for the infill of the panels: folded sheet tubes for the wall panels and flat sheets for the floor/ceiling panels. Figure 2b illustrates the components of the cardboard panel and the template used for fabricating the tubes. Eleven tubes of triangular section of dimensions 80 mm base and 80 mm height form each cardboard panel. The panel has a 577 x 564 mm facing sheet of cardboard on both sides. The flat sheets for the floor and ceiling panels do not need

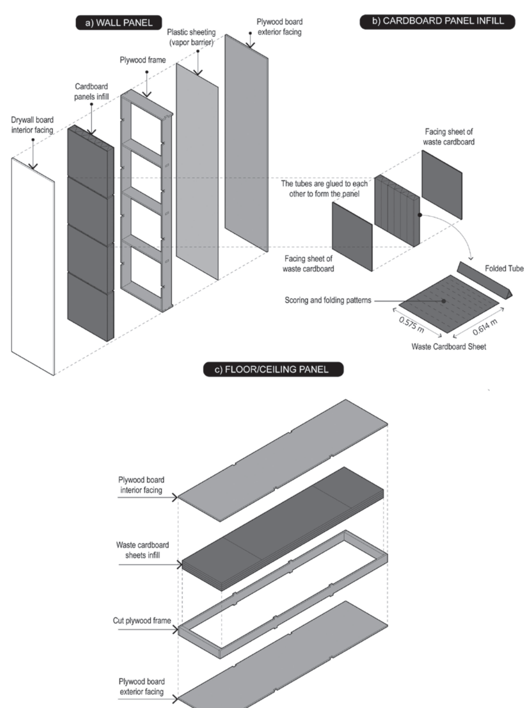

Figure 2: Main Components of the Panels (Author 2019)

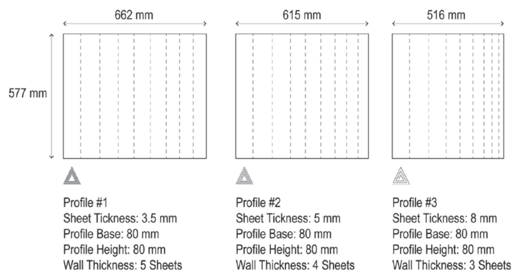

Figure 3: Waste Cardboard Sheet Templates (Author 2019)

templates and are layered one on top of each other inside the frame. This method allows the possibility of using sheets that are too small or too big for the tubes, increasing the reuse rate of the material. The exterior facing of the walls, for this prototype, is made of plywood boards of 18 mm on the exterior and 12 mm thick drywall boards on the interior with an additional plastic film on the exterior side that acts as a vapor barrier. Figure 2 illustrates each component of the panels.

1.3. PARAMETRIC DESIGN TOOLS

The folded sheet tubes for the wall panels are fabricated following the instructions provided by the parametric design tool presented in (Diarte, Vazquez, and Shaffer 2019a, 2019b). As stated in these papers, the tool facilitates the design of folded cardboard elements—in this case, triangular profile tubes—with sheets of different sizes and thicknesses. The tool receives two sets of data, the dimensions of the triangular profiles and the dimension of the sheets of waste cardboard. With this information, the tool generates different triangular profiles and calculates the best match with the available sheets of waste cardboard. Then, the tool visualizes the results showing the waste generated. Finally, the tool generates the instructions—templates that can be printed on paper or translated to paperboard or plywood—for cutting and scoring using hand tools. For this project, the parametric design tool was used to determine the cutting templates for three types of sheets of thicknesses 3.5 mm, 5 mm, and 8 mm. Figure 3 below illustrates the templates where the continuous lines represent cut lines and the dashed lines scoring lines.

2. ORGANIZATION OF THE WORKSHOP

The workshop had two primary goals. The first goal was to test the buildability of the prototype unit and the second goal to test the transferability of the system to local participants. Table 1 shows the workshop assessment framework prepared to organize the event. The table details how each goal was evaluated and documented.

Regarding the first goal, the focus was oriented in assessing how easy or difficult it was to fabricate the building parts and determine how adaptable is the system to the local situation. The task was subdivided into two parts: material collection and fabrication. The material collection consisted of obtaining the required supplies for the building, principally waste corrugated cardboard, plywood, and the necessary tools and fasteners. The variables measured to assess this task were cost, material supply time, and storage space needed.

To assess the buildability of the unit, we analyzed the capacities needed to execute each step of the workflow. Examples of questions this study sought to answer were:

- What type of equipment and tools are needed, and what are the specific requirements in terms of infrastructure?
- How many people are required to complete the workflow?
- What skills are they required to have?
- How much time is required to train the participants to use the space, equipment, and tools?
- How much space is needed to set up all the components of the workflow safely?

To evaluate if the system is easy to transfer or not, the experiment looked at the next elements:

- How easy or difficult it was for the participants to understand the fabrication instructions
- How much time was invested on each part of the workflow to fabricate and assemble the panels
- What was the quality of the outcome (e.g., the accuracy of the parts, joints, weight, and steadiness of the panels)

At the end of the workshop, the participants answered a questionnaire previously prepared to try to collect information to answer these questions. The questionnaire's goal was to document the participant's experience during the week and inquire how likely are they to use part of what they learned.

2.1. VALUE OF FULL-SCALE MOCK-UPS

This study is based on the fabrication of a full-scale prototype structure or mock-up. The use of full-scale mock-ups in architecture and engineering facilitates several aspects of the process of testing the construction of buildings or part of them (Designing Buildings Wiki n.d.). It is an essential process for testing innovative applications of construction materials and building systems. This process allows researchers/designers to identify potential problems, limitations, or constraints. Mock-ups are also useful to get feedback from the participants about the proposed fabrication workflow and the technology itself.

Workflow Components→	Material Collection	Fabrication of Building Parts	Assembly of the Prototype Bay Structure
Sub-components	• Material Collection (timber and waste cardboard) • Waste Cardboard Sorting • Waste Cardboard Documentation	• Design of Building Parts (floor and wall panels) • Fabrication of Building Parts (floor and wall panels)	• Building Parts Transportation • Building Parts Assembly • Sheathing Installation
	↓	↓	↓
Goal →	To determine how feasible it is to get cardboard and how much of the cardboard collected is useful	To assess how easy it is to understand the fabrication process and its affordability	To evaluate the practicability of the assembly process and how many people are needed.
Assessment Procedure / Feature Evaluated →	- *Quantification of time spent collecting and documenting* - *Quantification of the amount of material collected: How much was recovered and how much was discarded?*	- *Easy understanding of the fabrication instructions* - *Use of material/waste* - *Time spent in the fabrication* - *Workforce* - *Workspace* - *Tools and hardware used* - *Quality of the building parts (geometry, weight, shape accuracy)*	- *Easy understanding of the assembly instructions* - *Easy of transportation* - *Time spent in the assembly* - *Quality of the assembly (accuracy of the joins, the steadiness of the structure)*
Questions addressed →	- *How easy is it to get the waste cardboard?* - *How much does it cost to get the material needed?* - *Is waste cardboard low-cost?*	- *How much time takes to fabricate the building parts?* - *How many people are needed for the fabrication?* - *How easy is it to fabricate the parts?* - *Can this be made with low-construction skills people?*	- *How much time does it take to assemble the unit?* - *How easy is it to assemble the unit?*
Outcome / Deliverable →	Receipts detailing the amount of material provided	Prototype unit structure, a survey completed by the participants of the construction workshop evaluating each one of the steps mentioned above, notes, and visual documentation of the construction process.	
Participants →	Local NGO	- Four participants (collectors of waste cardboard with little or no experience with construction) - Two assistants (student from the architecture school)	
Data Collection Procedure →	On-site Survey	- Audio, video, notes, and photography - Survey at the end of each part	

Table 1: Workshop Assessment Framework

Previous research done on cardboard architecture showed that this type of approach allows the parties involved to test the manufacture of the components and the assembly process. An example of this is the project for the Westboro School in Essex, the UK, designed by Cottrell & Vermeulen and Buro Happold Consulting Engineers in 2004 (Cripps 2004). The school building's mock-up was one-sixth part of the whole building, and the research team confirmed the importance of the mock-up to "save money and time." In general, researchers in the area of residential building construction value full-scale mock-up testing because this provides information about usefulness, safety, and quality (Memari et al. 2014, 28).

2.2. LIMITATIONS OF THE WORKSHOP

Although the outcomes of this workshop are beneficial for further improvement of the building system, the results cannot be used to draw statistical analysis. This is because of the limited scope of the experiment and the reduced number of participants. Another factor that cannot be assessed here is the livability of the prototype structure or how the building responds over time. Although the full-scale mock-up shows the real scale of the building and the participants can express their impressions about it, it is not possible to evaluate with precision factors such as comfort, safety, functionality, stability against the elements, and privacy in the long-term.

2.3. THE PARTICIPANTS

The goal of the project is to design a housing system addressed for people who cannot afford to build their houses using standard construction materials—e.g., timber, masonry, steel, and concrete—but have direct access to waste corrugated cardboard. Consequently, the main criteria for including participants were the next.

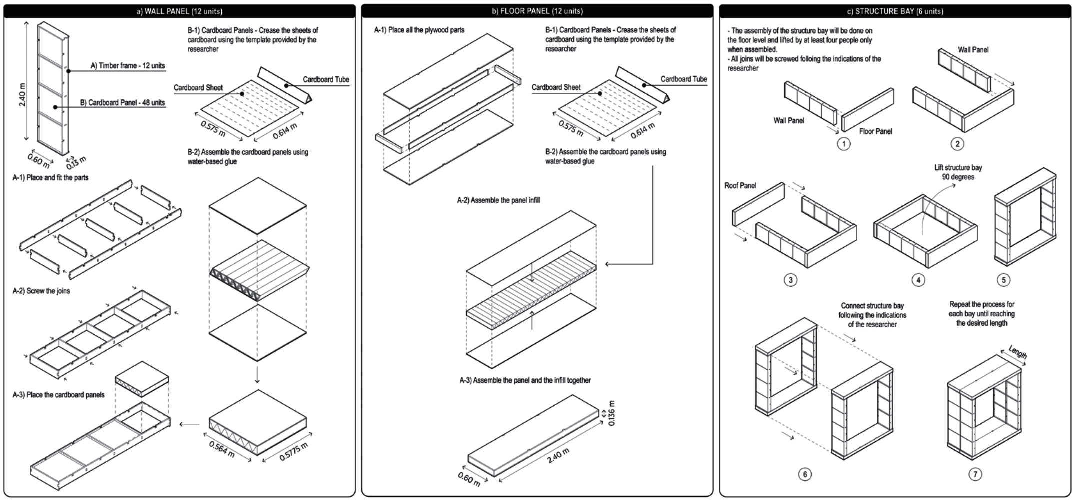

Figure 4: Fabrication Instructions (Author 2019)

Firstly, the participants should have formal or informal experience as collectors of waste cardboard, so they can learn about the opportunities for using this material. Secondly, the participants should have little or no experience at all in construction, so the researcher could test how easy it is to understand the system.

2.4. FABRICATION INSTRUCTIONS AND LIVE DEMOS

Figure 4 shows the instructions handed to the participants. The printed fabrication instructions summarize the fabrication of wall, floor, and ceiling panels. The instructions include step-by-step instructions for the fabrication of the parts and the assembly of the structure bay and the consequent assembly of the whole unit. These instructions are meant to guide the participants in the process; however, live demos showing each step of the process are also necessary.

3. RESULTS

3.1. THE WORKSHOP'S LAYOUT

One of the factors that this experiment sought to evaluate was to identify the infrastructure needed to operate the fabrication workflow. In this regard, the workshop was held at the Center for Research, Development, and Innovation (CIDi) located at the School of Architecture, Design, and Arts at the National University of Asuncion (FADA-UNA). The workshop occupied a multifunctional area inside the CIDi destined for exhibitions, lectures, and workshops that offered easy access for both participants and suppliers.

Figure 5 shows the spatial organization of the workshop emphasizing the following: a) woodworking area (25 m²); b) area for the fabrication of cardboard parts and assembly (70 m².); c) lectures and lunch (20 m²); d) plywood and drywall storage area (20 m²); and e) discarded cardboard storage area (10 m²). An additional area used was located at the Industrial Design's woodshop at FADA-UNA where the shop's staff precut part of the wood frames. Overall, without considering the area of the woodshop, the workshop occupied around 145 m². of space. Besides having enough space and the conventional infrastructure needed to operate power tools, no other special equipment or infrastructure was required to develop the work.

3.2. MATERIALS USED

The local NGO *ProCicla* provided 1.2 tons of sheets of waste cardboard in two batches in two different days a week before the workshop. The first batch of 0.55 tons on August 5 and then 0.65 tons on August 8. The material came from a clothing store, and it was stored at the location of the workshop occupying around 30 m2. Around 5% of the material was discarded because it was torn or contaminated with food or liquids. No documentation of individual cardboard sheets was made due to the amount of time this was going to take. What was not discarded was roughly classified by size, but the elevated level of variability of the sheets made it challenging to assess with precision the quantity and size of sheets. Later in the paper, it will be explained how the sheets were selected to fabricate the building parts. Other materials used for the construction of the unit included wood (plywood boards and rafters), drywall, plastic sheets for the vapor barrier, and fasteners.

Table 2 shows the summary statistics for materials used in the construction of the unit. What stands out in the table is the low-weight and the low-cost of the

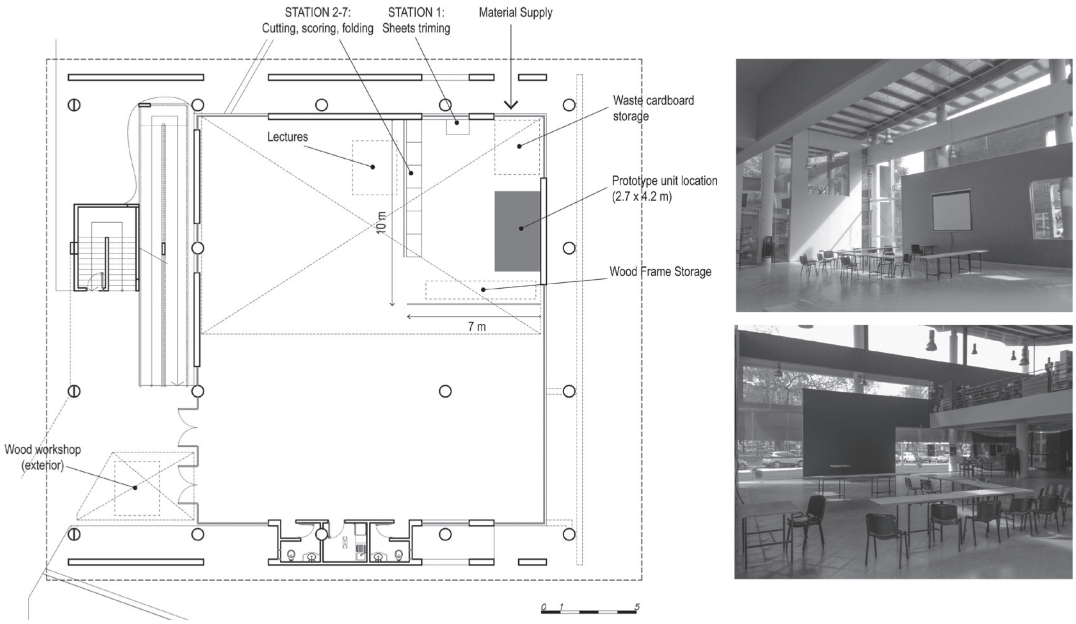

Figure 5: Layout of the workshop and views of the interior space at the CIDi. (Author 2019)

cardboard sheets (15% of the total weight and 8% of the total cost) compared to the volume occupied by this material (almost 60% of the total volume is occupied by cardboard). This feature of cardboard has a positive influence on the total weight and the total cost of materials. However, the impact of timber on the total weight and total cost of materials is something to be considered carefully (65.62% of the total weight and 78% of the total cost of materials). This impact can also be positive if we think it could increase the stability of the structure against potential horizontal forces (wind and earthquakes). On the other hand, the impact on the cost forces to develop strategies to reduce the amount of timber or replace it with something less expensive.

Table 3 shows the budget composition of the unit, including items such as hardware, fasteners, tools, labor, transportation, and the materials mentioned above. This budget does not include municipal permit costs and designer's honoraria, foundation, doors, windows, finishing, or any electrical, heating, cooling, and ventilation installations. Although the analysis of this budget may be somewhat limited because it does not include these items, it is useful to observe the impact of each item. In this sense, the most significant information observed in this figure is, again, the high impact of materials in the budget, where timber is the most expensive item. Transportation costs were minimal, mostly because the fabrication and assembly were done at the same location. The incentives paid to the participants were equivalent to the minimum wage established by law in Paraguay, which-also applies to low-ranking workers in local construction companies. The impact of labor cost is within the usual percentage (25-30%).Another interesting aspect found in the analysis of the cost of the unit built in this workshop is revealed when the cost per m2. of the unit is compared to the one of standard housing construction in the local context. The cost of this unit was $183 per m² and the

Material		By Volume (m3)	%	By Weight (tons)	%	By Cost (US$)	%
Timber	Plywood	2.55	38.39%	0.54	62.12%	$1,005.56	74%
	Studs	0.03	0.38%	0.03	3.50%	$59.55	4%
Cardboard		3.82	57.59%	0.13	15.01%	$111.11	8%
Drywall		0.24	3.64%	0.17	19.14%	$82.49	6%
Plastic Sheet		0.00	0%	0.00	0.23%	$7.58	1%
Fasteners		0.00	0%	0.00	0%	$99.84	7%
Totals		**6.64 m3**		**0.86 tons**		**$1,366.12**	

Table 2: Summary of materials used in the construction of the unit

cost of an equivalent construction made with traditional building materials, according to current reports on building construction in Asuncion, is around $146 per m². (Mandu'a 2019). The main reason the cost of the unit is higher is probably due to the high cost of the timber. Nevertheless, several other factors can be used to compare both systems that are not being considered here, such as the environmental impact in the long term, that could factor in as an advantage for using waste cardboard and wood frames.

Item	Cost	%
Hardware, Fasteners & Tools	$176.37	9.53%
Labor	$475.84	25.72%
Materials	$1,192.21	64.45%
Transportation	$5.35	0.29%
	$1,849.77	

Table 3: Budget Composition of the Unit

3.3. PARTICIPANTS

The recruitment process was done through direct contact with people related to the collection of urban waste in the metropolitan area of Asuncion. *Soluciones Ecologicas SRL*, a private company in Asuncion dedicated to collection and waste management, facilitated the contact with a group of collectors with whom they work. Four people, two females and two males, participated in the workshop for five consecutive days. The educational attainment of the participants was high school graduate or equivalent. Of the four participants, one had experience working for two years in a construction company as laborer assisting in the construction of masonry walls. The other two had informal experience on self-construction of their own house – masonry walls and metal sheet roofing. Although all of them had informal experience working in the collection of waste cardboard and other recyclables, none of them had ever used cardboard as a construction material. Table 4 summarizes the information of the participants.

3.4. FABRICATION AND ASSEMBLY WORKFLOW

The diagram in figure 6 shows the fabrication workflow of the workshop. The workflow consisted of two parts: the fabrication of cardboard panels and the fabrication of wood frames. Each part occupied a different location; the cardboard panels were fabricated in the space arranged at the CIDi, and the wood frames were cut at the woodshop. The researcher guided the participants in the fabrication of the cardboard panels and the assembly of the panels. The workshop took five days working from 9 am to 5 pm approximately.

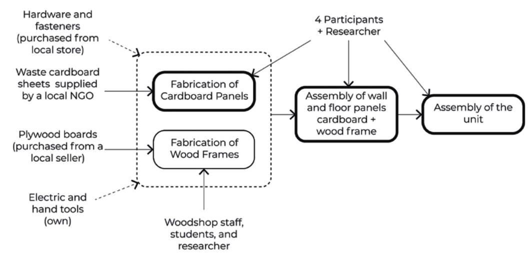

Figure 6: Fabrication Workflow Diagram (Author 2019)

On the first day of the workshop, after introducing the participants to the goals of the research, the researcher presented the fabrication instructions and handed printed copies in the form of booklets to the participants so they could consult them whenever they. During the introduction, the researcher explained the workflow, showing the working stations, and the available tools. The participants worked only in the fabrication of cardboard panels and the assembly of the panels (steps 7-a to 7-h in Fig. 7 and steps 8-a to 8-d in Fig. 8). Since the participants did not have any experience cutting wood and to avoid accidents, the researcher, together with the woodshop staff and interns, precut the timber frames before the workshop.

Fabrication of Cardboard Panels

Steps 7-a to 7-h in figure 7 illustrates the fabrication process of cardboard panels. The process started with selecting the sheets that were not torn or contaminated

Participant #	Gender	Age Range	Formal Experience in Construction	Informal Experience in Construction
Participant #1	Female	40-45	No	Yes: Self-construction of own house
Participant #2	Male	45-50	No	Yes: Self-construction of own house
Participant #3	Female	20-25	No	No
Participant #4	Male	50-55	Yes: 2 years working as a laborer in a building company	Yes: Self-construction of own house

Table 4: Participant's Basic Information

with food or liquids and having the minimum required dimension for the tubes and facing (step 7-a). In step 7-b, the selected sheets were trimmed to the indicated dimensions. Next, in step 7-c, the participants scored the sheets following a pre-cut template. For this task, the participants used a conventional knife and wood templates made of ¼ inches plywood. In Step 7-d, the participants folded the sheets manually to form the tube adding water-based adhesive to hold it.

Step 7-e consisted of spraying a solution of Boron and water (1:10) for fungal and insect attack protection treatment. Boron is a chemical component commonly used in agriculture that has insecticidal and fungicidal properties. According to previous research by Kaminski et al. published in 2016, it is the most convenient chemical used to treat bamboo. The researcher decided to replicate the used of this chemical for the preservation of cardboard, considering certain resemblance of both materials—cardboard is made of fibrous and natural materials similar to bamboo.

In step 7-f, the participants assembled the cardboard panels. Each panel used eleven cardboard tubes and two facing sheets that were glued together using water-based adhesive. The team fabricated a total of 561 cardboard tubes and cut 102 facing sheets. Both the tubes and the facing sheets were employed to fabricate 51 cardboard panels of dimensions 565 x 577 x 100 mm. Figure 7-g shows a participant trimming the cardboard panel using a handsaw to correct some inconsistencies in its dimensions. It also shows two participants placing the cardboard panels inside the wood frame. The cardboard panels were placed applying manual pressure and did not need any adhesive.

Figure 7: Fabrication Process for the Cardboard Panels (Author 2019)

Assembly of Building Parts

Figure 8-a to 8-d shows the process of assembling the building parts. Figure 8-a shows the placement of two studs on the floor. Figure 8-b shows the procedure for assembling the floor panels. The top image of figure 8-b shows the uncovered and empty floor panel on which the sheets of cardboard that were not used for the tubes were placed. The bottom image of the same figure shows all floor panels placed on top of the studs. Each panel was joined to the studs and to each other by using conventional screws. Images on 8-c show the participants placing the plastic sheeting for vapor barrier protection. The bottom image shows a wall panel where one of the niches will be used for placing a window. Figure 8-d showed in the top image when the participants were placing the ceiling panel, and the bottom view is a general view of PU2 on the last day of the workshop, when the team managed to assemble the unit partially.

Figure 8: Assembly Process of Floor, Wall, and Ceiling Panels (Author 2019)

DISCUSSION

What were the lessons learned from this workshop?

The first goal was to analyze how feasible it is to get enough waste cardboard to build the PU2 and how much of the cardboard collected is used for the project. The answer to the first part is affirmative; getting the material was relatively uncomplicated. Regarding the second part, the project used around 80% of the 1.2 tons supplied by ProCicla, and the remaining 20% were sent back for free to recycling—the leftover could have even been resold to recycling companies for the same price they were purchased.

However, there are a few aspects to consider that could have a significative impact on the project. The first consideration regards who provides the material. In this sense, the study found that there are three ways of obtaining waste cardboard in the context of Asuncion and the metropolitan area: a) from self-employed cardboard collectors; b) from private companies or NGO's dedicated to waste management, including the collection of recyclables; or c) directly from cardboard factories.

Initially, for this workshop, the plan was that self-employed collectors would provide the waste cardboard needed. Nevertheless, this option was discarded because the collectors could not get enough material in such a short time—just one week before the workshop—and they could not guarantee the quality of the material either because the material they usually get comes directly from the streets and dumpsters. To make this possible, the period for collection and selection must be longer, and this was not possible for this workshop.

In the second option, which was the one used for this workshop, the time was not inconvenient~~;~~ and the quality was acceptable, because the supplier collects waste cardboard sheets weekly from large clothing stores and commercial centers. In this kind of place, the material is handled generally in interior spaces, and it is not exposed to the elements, assuring a relatively decent quality that facilitates its reuse—e.g., the sheets are not wet and torn. The cost of the waste cardboard provided by the NGO was the same as that of the collectors—around 8 cents of a dollar per kilogram.

The third option, getting the material from cardboard factories, was discarded because although these companies could have provided high-quality waste cardboard at the same price as the other suppliers, the material represents another kind of sample. Waste cardboard from factories is usually leftover from template cuts that are small in size.

The experience of this workshop suggests that, although the material is inexpensive and relatively easy to get, it is critical to evaluate who will provide the material and how to manage this component. The characteristics of the material—e.g., quality, quantity, and size—vary depending on who is the provider. On the other hand, storing and handling waste cardboard sheets is an unclean task that requires protective equipment and clothing, and a large and well-ventilated covered area to avoid working in a polluted space.

The second goal of the workshop was to assess how easy it is to understand the fabrication process and test how affordable the system is in the local context. To evaluate how easy it is to understand the process, it is essential to consider separately the two phases of the fabrication workflow shown previously in figure 5. For the first phase fabrication of cardboard panels, contrary to the expectations, the participants did not pay as much attention to the printed handouts with visual instructions as to the live demos. According to what they expressed during the interview at the end of the workshop, they did not use the printed handouts because they are not used to following graphic instructions.

The live demos, on the other hand, were easier to follow because they could see everything in full-scale and ask questions of the instructor if needed. This situation is understandable considering the subjects did not have experience participating in this kind of activity; however, it raises the question the best approach and the appropriate supporting materials for teaching people how to build using this system.

In general, the fabrication of the cardboard panels was an uncomplicated task for the participants, and they confirmed this during the interview. Some of the factors they mentioned as positive during the process of fabricating the cardboard panels were, for instance, the workability of cardboard (e.g., easy to handle and lightweight), the familiarity with the tools (e.g., knife, wood templates, adhesive, etc.), and the easiness of the step-by-step process. The participant manifested their surprise regarding the potential of the material and showed interest in other possible applications.

Regarding the second phase~~,~~ fabrication of the wood frames, it is essential to highlight that the participants did not have contact with this process for the reasons mentioned earlier in this paper. The instructor and woodshop assistants managed the process of cutting the parts for the frames. In order to enable the participants to operate the tools, it is necessary to implement a more extended training period which was not possible for this workshop. The participants did assemble the wood frames, though, and the process was not as easy as expected. The main issue was, according to them, the "complicated design of the parts" with different pieces and the many joints.

Regarding the affordability of the system, the workshop has shown that timber has a substantial impact on the total cost of the prototype (78% of the total cost of materials). This factor will force us to explore alternative ways to reduce the amount of timber and increase the amount of waste cardboard in the design of the prototype. A current study is looking into the design of the wall panels and testing the mechanical performance of waste cardboard panels of different thicknesses to decrease the quantity and thickness of the plywood elements.

Another goal of the workshop was to evaluate the practicability of the assembly process and the number of-people needed for this task. Overall, learning how to assemble the wall and floor panels requires training and practice to achieve quality. Although the workshop presented an excellent opportunity to test this, and the participants did learn how to do it, the available time did not allow them to finish the assembly of the whole PU2 and thus to reach the optimal quality of finishes. With respect to the number of people needed for the task, it was indeed possible to build this unit with four participants; however, the number of people needed to scale up the production is still uncertain, and cannot be determined with the results of this workshop.

CONCLUSION

The purpose of the construction workshop presented in this paper was to test the feasibility of the panelized building system using sheets of waste cardboard and plywood mainly. In this paper, the author presented the design concept of a prototype unit, describing the process for fabricating its parts, the methodologies planned to develop the construction workshop, and discussed the main lessons learned from the experience. The incorporation of local collectors of waste cardboard as participants of the workshop allowed the researcher to test the system working with potential users of the technology. Overall, the workshop has shown the feasibility of the fabrication of panels using sheets of waste cardboard and simple tools, and the usefulness of digital design tools to provide the cutting/scoring instructions for the participants. The relative feasibility of the assembly system and the substantial impact of the use of plywood in the total cost were additional factors analyzed during this experiment. Further research is being developed to decrease the amount of timber and increase the use of waste cardboard, as well as to simplify the fabrication instructions.

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REFERENCES

Ayan, Özlem. 2009. "Cardboard in Architectural Technology and Structural Engineering." *ETH Zurich*. https://doi.org/http://dx.doi.org/10.3929/ethz-a-006080626.

Cripps, Andrew. 2004. "Cardboard as a Construction Material: A Case Study." *Building Research & Information* 32 (3): 207–19.

Designing Buildings Wiki. n.d. "Samples and Mock-Ups for Construction." Accessed April 10, 2019. https://www.designingbuildings.co.uk/wiki/Samples_and_mock-ups_for_construction.

Diarte, Julio, and Marcus Shaffer. 2018. "Urban Recycling Intervention: Devising Low-Cost Tools for Transforming Old Corrugated Cardboard into Building Elements and Construction Materials." In *10th International Conference on the Environmental and Technical Implications of Construction with Alternative Materials*, edited by Pentti Lahtinen and Ville Raasakka, 362–66. Tampere: ISCOWA The International Society for the Environmental and Technical Implications of Construction with Alternative Materials.

Diarte, Julio, Marcus Shaffer, and Esther Obonyo. 2019. "Developing a Panelized Building System for Low-Cost Housing Using Waste Cardboard and Repurposed Wood." In *Proceedings of 18th International Conference on Non-Conventional Materials and Technologies – IC NOCMAT 2019 Nairobi, Kenya, 2019*, edited by Normando Perazzo Barboza, 155–66. Nairobi: Universidade Federal de Paraiba Brazil.

Diarte, Julio, Elena Vazquez, and Marcus Shaffer. 2019a. "Tooling Cardboard for Smart Reuse: A Digital and Analog Workflow for Upcycling Waste Corrugated Cardboard as a Building Material." In *Computer-Aided Architectural Design. "Hello, Culture,"* edited by Ji-Hyun Lee, 384–98. Singapore: Springer Singapore. https://doi.org/https://doi.org/10.1007/978-981-13-8410-3_27.

Diarte, Julio, Elena Vazquez, and Marcus Shaffer. 2019b. "Tooling Cardboard for Smart Reuse: Testing a Parametric Tool for Adapting Waste Corrugated Cardboard to Fabricate Acoustic Panels and Concrete Formwork." In *Architecture in the Age of the 4th Industrial Revolution - Proceedings of the 37th ECAADe and 23rd SIGraDi Conference*, edited by J Sousa, J Xavier, and G Castro Henriques, 2:769–78. Porto: eCAADe, SIGraDI, FAUP. http://papers.cumincad.org/cgi-bin/works/paper/ecaadesigradi2019_197.

IADB. 2015. "Solid Waste Management in Latin America and the Caribbean." *Inter-American Development Bank*. https://publications.iadb.org/handle/11319/7177#sthash.7bODjAHq.dpuf.

Kaminski, Sebastian, Andrew Laurence, David Trujillo, and Charlotte King. 2016. "Structural Use of Bamboo. Part 2: Durability and Preservation." *The Structural Engineer: Journal of the Institution of Structural Engineer* 94 (10): 38–43.

Latka, Jerzy F. 2017. “Paper in Architecture: Research by Design, Engineering, and Prototyping.” The Delft University of Technology. https://doi.org/10.7480/abe.2017.19.

Mandu’a, Revista. 2019. “Casa Mandu’a - Vivienda Modelo 1.” *Revista Mandu’a*, 2019. https://issuu.com/a.arza/docs/mandua__digital_octubre438.

Memari, Ali M., Patrick H. Huelman, Lisa D. Iulo, Joseph Laquatra, Carlos Martin, Andrew McCoy, Isabelina Nahmens, and Tom Williamson. 2014. “Residential Building Construction: State-of-the-Art Review.” *Journal of Architectural Engineering* 20 (4): B4014005. https://doi.org/10.1061/(asce)ae.1943-5568.0000157.

Pohl, Almut. 2009. “Strengthened Corrugated Paper Honeycomb for Application in Structural Elements.” *ETH Zurich*. https://doi.org/http://dx.doi.org/10.3929/ethz-a-006060041.

Salado, Gerusa de Cássia. 2011. “Painel de Vedação Vertical de Tubos de Papelão: Estudo, Proposta e Análise de Desempenho.” Ph.D. Thesis, Universidade de Sao Paulo.

Silpa Kaza, Lisa Yao, Perinaz Bhada-Tata, and Frank Van Woerden. 2018. *What a Waste 2.0 A Global Snapshot of Solid Waste Management to 2050*. 1st ed. Washington DC: International Bank for Reconstruction and Development / The World Bank. https://doi.org/10.1596/978-1-4648-1329-0.